Development of a Mathematical Model for ‘Hayward’ Kiwifruit Softening in the Supply Chain

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Food Technology at Massey University, New Zealand

Zhao Junyu, Matthew

2017

Abstract

Fruit loss is a major concern to the kiwifruit industry as it incurs a high cost to monitor and remove over soft or rotten fruit to meet export standards. Kiwifruit is exposed to various temperature scenarios due to different packhouse cooling practices, and temperature control is difficult to maintain throughout the supply chain. Fruit pallet temperatures are wirelessly monitored in the supply chain. This time temperature data provides valuable rich information which could be used to predict kiwifruit quality.

In the laboratory, green 'Hayward' kiwifruit were exposed to industry coolchain scenarios to investigate their influence on fruit firmness in subsequent storage. Cooling rate and storage temperature were identified to affect fruit firmness and chilling injury development significantly, where accelerated softening and increased chilling injury development was observed in late storage (> 100 d) when fruit were cooled directly to 0 °C. However, when fast cooled fruit were stored at 2 °C instead of 0 °C, low incidence of chilling injury was observed. The influence of cooling rate and storage temperature on kiwifruit quality suggests that industry should focus on the management practices adopted by packhouses in order to maintain acceptable quality after long term storage. A proportion of the firmness data results were used to develop a mechanistic style mathematical model of kiwifruit softening. Kiwifruit softening was mathematically described based on the correlation with starch degradation, breakdown of cell wall structure, and a description of the incidence of chilling injury development during storage. The model inputs consist of solely commonly collected at-harvest attributes: firmness, dry matter and soluble solids content and time-temperature data. Applying at-harvest attributes as model inputs enabled a capability to predict different softening curves as influenced by fruit maturity, and grower line differences. The developed model demonstrated promising softening prediction with mean absolute errors (MAE) between 0.8 to 2.1 N when fruit were exposed to fluctuating temperatures and cooling profiles. A logistic model was used to estimate the proportion of chilling injured fruit. Based on the given time temperature information, the logistic model was able to predict the proportion of chilling injured fruit reasonably well ($R^2 = 0.735$). This chilling injury prediction was subsequently used to adjust the softening prediction during the late storage period (>100 d). Model validation was performed using the remaining data, identifying a lack of fit in both the rapid (MAE of 20.8 N) and gradual (MAE of 8.0 N) softening phase. The lack of fit in the rapid softening phase is proposed to be explained by the presence of an initial lag phase in softening which the developed model is unable to predict. The magnitude of firmness associated with starch content and cell wall integrity heavily influenced the lack of fit in the gradual softening phase. Fixing the initial amount of firmness associated to cell wall integrity to be constant for all maturities and grower lines improved the softening prediction.

Overall, this thesis contributes to the challenge of predictively modelling kiwifruit quality in the supply chain. However, there are still many opportunities for improvement including introducing the influence of: variation within the same batch; fruit maturity on chilling injury development; ethylene in the environment; pre-harvest management practices and extending the model to have more focus on high temperature conditions such as those experienced in the marketplace. Conducting studies on: the effect of curing on kiwifruit; using non-destructive techniques to provide information to help define model parameters for prediction; effect of high temperature exposure on kiwifruit softening are possible opportunities that may contribute to enable better prediction of kiwifruit quality in the supply chain in the future.

Acknowledgments

I wish to thank my supervisors, Dr. Andrew East and Prof. John Bronlund for the incredible amount of time and support given to me during my PhD. I greatly appreciate their positive feedback, continuous efforts and always encouraging me through tough times.

I would like to say many thanks to Peter Jeffery for his help when I had troubles in either my laboratory work or technical issue with computer and Sue Nicholson for her help and patience in assisting me in experimental planning and during my time in the laboratory. I am also thankful to Byron, Warwick and Gary for their technical support.

Heaps of thanks should go to Zespri International Ltd for the fellowship and supplying kiwifruit for this study. I am also thankful to Massey University for providing extra funding to relief my financial issues especially during my last year of study.

I am indebted to many of my friends and colleagues for their help and support throughout my studies in New Zealand. They are Tamarath (An) Pranamornkith, Gayani, Khairul, Pilirani, Jantana, Li Mo, Abdul and Srikanth. Special thanks to Ivana, Wensheng, Grace, Eileen, Seng Guan and Jordan for being an asset of good friends during my time in New Zealand.

Special thanks to my mother and father for their encouragement and appreciate my siblings (Roy, Vyennus and Dominic) for taking care of the family when I am away for my studies. Finally, I would like to thank Jenny, who is a very special person of my life. I am grateful for her continuous encouragement and support during all tough stages in my studies and always there to listen to my problems. I appreciated all the time you spent waiting for me to return to Singapore.

Table of contents

List of Figures

List of Tables

Nomenclature

Symbol	Definition	Units
a	Correlationship between starch and firmness	N %$^{-1}$
AHU_{α}	AHU when 50 % of chilling injured fruit is reached	°C d
AHU	Accumulated heat unit	°C d
B	Soluble solid contents	°Brix
B_0	Initial soluble solid content	°Brix
B_{final}	Final soluble solids content	°Brix
F_{CI}	Lowest firmness measured	N
CI	Proportion of chilling injured fruit	%
CI_{max}	Maximum proportion of chilling injured fruit	%
CI_{min}	Minimum proportion of chilling injured fruit	%
D_m	Dry matter content	%
$E_{a,s}$	Activation energy for starch breakdown	J mol^{-1}
$E_{a,p}$	Activation energy for breakdown of cell wall structure	J mol^{-1}
F	Fruit firmness	N
F_0	Initial fruit firmness	N
F_A	Firmness correlated with starch degradation	N
F_B	Firmness contributed by cell wall component	N
F_{Fix}	Underlying basal firmness	N
F_{pred}	Predicted fruit firmness	N
F_{soft}	Predicted soft fruit firmness	N
k_b	Rate constant of accumulation of soluble solids content	d^{-1}
k_s	Rate constant of starch breakdown	d^{-1}
$k_{s,ref}$	Rate constant of starch breakdown at T_{ref}	d^{-1}
k_w	Rate constant of the breakdown of cell wall structure	d^{-1}
$k_{w,ref}$	Rate constant of the breakdown of cell wall structure at T_{ref}	d^{-1}
R	Universal gas constant, 8.314	J mol^{-1}K^{-1}
S	Starch content	%
S_0	Initial starch content	%
t	Time	d
T	Temperature	°C
T_{abs}	Temperature in absolute	K
T_{ref}	Reference temperature at 20 °C	K
T_b	Base temperature	°C
μ	Rate constant of chilling injury development	d^{-1}

Symbol	**Definition**
	Storage conditions
TB 9	Break in temperature control after 9 weeks of storage
TB 15	Break in temperature control after 15 weeks of storage
HT	High temperature treatments
DH	Different humidity conditions at 30 °C
$R_{12h,0}$	Fruit rapidly cooled to 0 °C within 12 hours
$R_{12h,2}$	Fruit rapidly cooled to 2 °C within 12 hours
$D_{3d,0}$	Fruit directly cooled to 0 °C within 3 days
$G_{2w,0}$	Fruit gradually cooled to 0 °C within 2 weeks
$C_{1w,0}$	Fruit rapidly and gradually cooled to 0 °C within 1 week
$C_{1w,2}$	Fruit rapidly and gradually cooled to 2 °C within 1 week